Low-Energy Proton Testing Methodology

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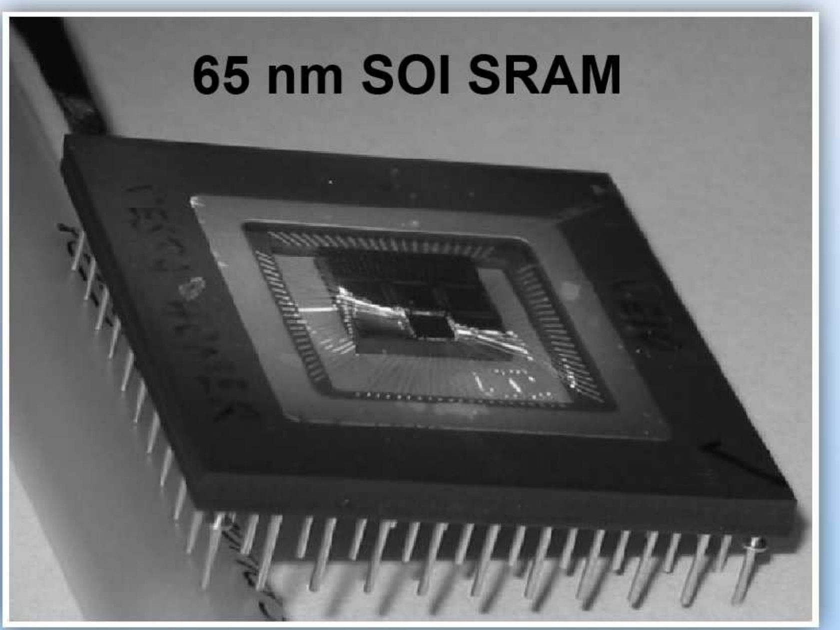
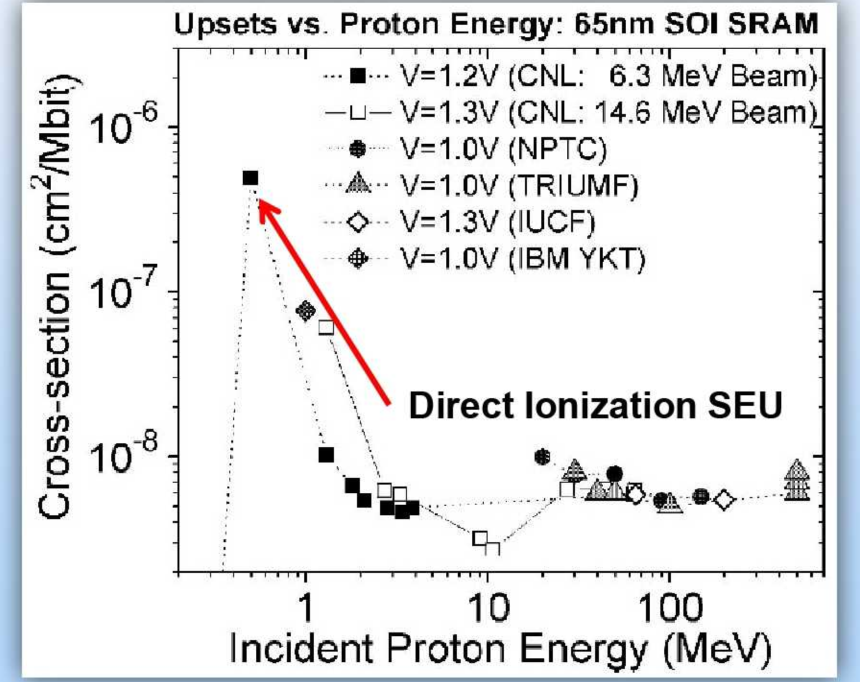
Overview

- Sub-100 nm technologies show SEU sensitivity to low-energy protons
- Testing challenges associated with low-energy proton beams
- Outline of current best practices
- Is it low-energy protons or high-energy light ions?
- Summary

Moving to Low-Energy Protons

- **Proton testing is an integral part of accelerated ground testing and single-event effects evaluation**
  - **Will continue to use high-energy (> 60 MeV) proton beams**
  - **New interest in low-energy (< 5 MeV) proton beams**

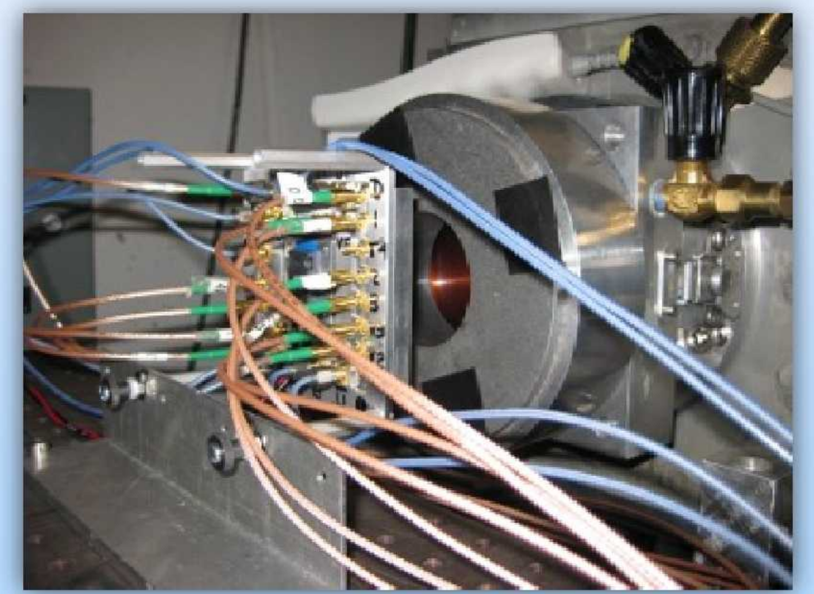




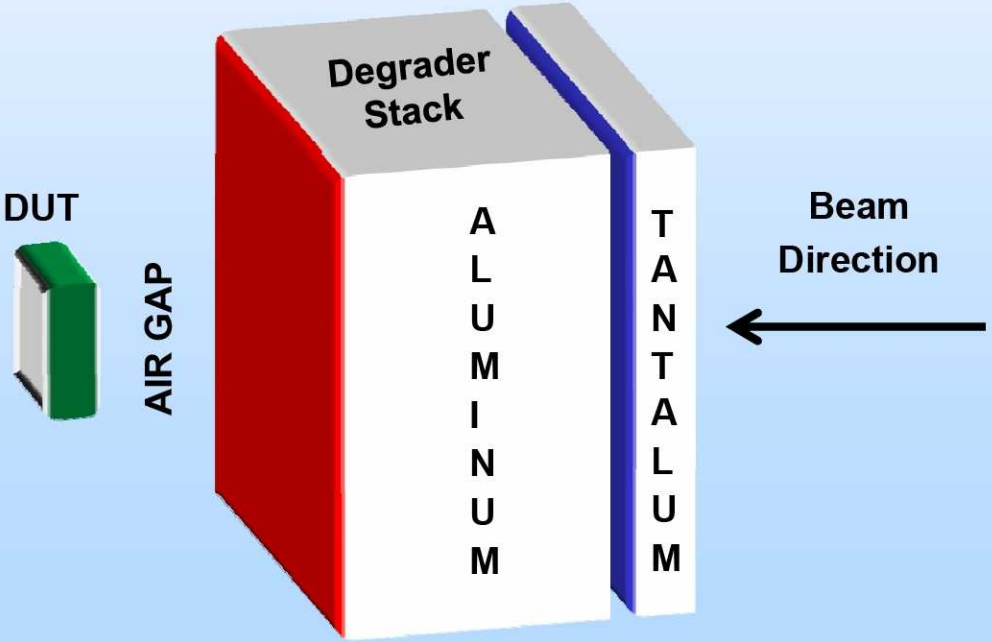
D. F. Heidel *et al.*, "Low-Energy Proton Single-Event-Upset Test Results on 65 nm SOI SRAM," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 6, pp. 3394-3400, Dec. 2008.

Low-Energy Testing Challenges

- **Low proton energy leads to several important topics**
  - **Where's the Bragg peak?**
  - **Tune the beam or degrade it**
  - **Topside testing (wire-bonded DUT) or backside (C4)**
    - **Focus mostly on backside testing; is the die thinned?**
  - **Straggling, which affects both range and energy**

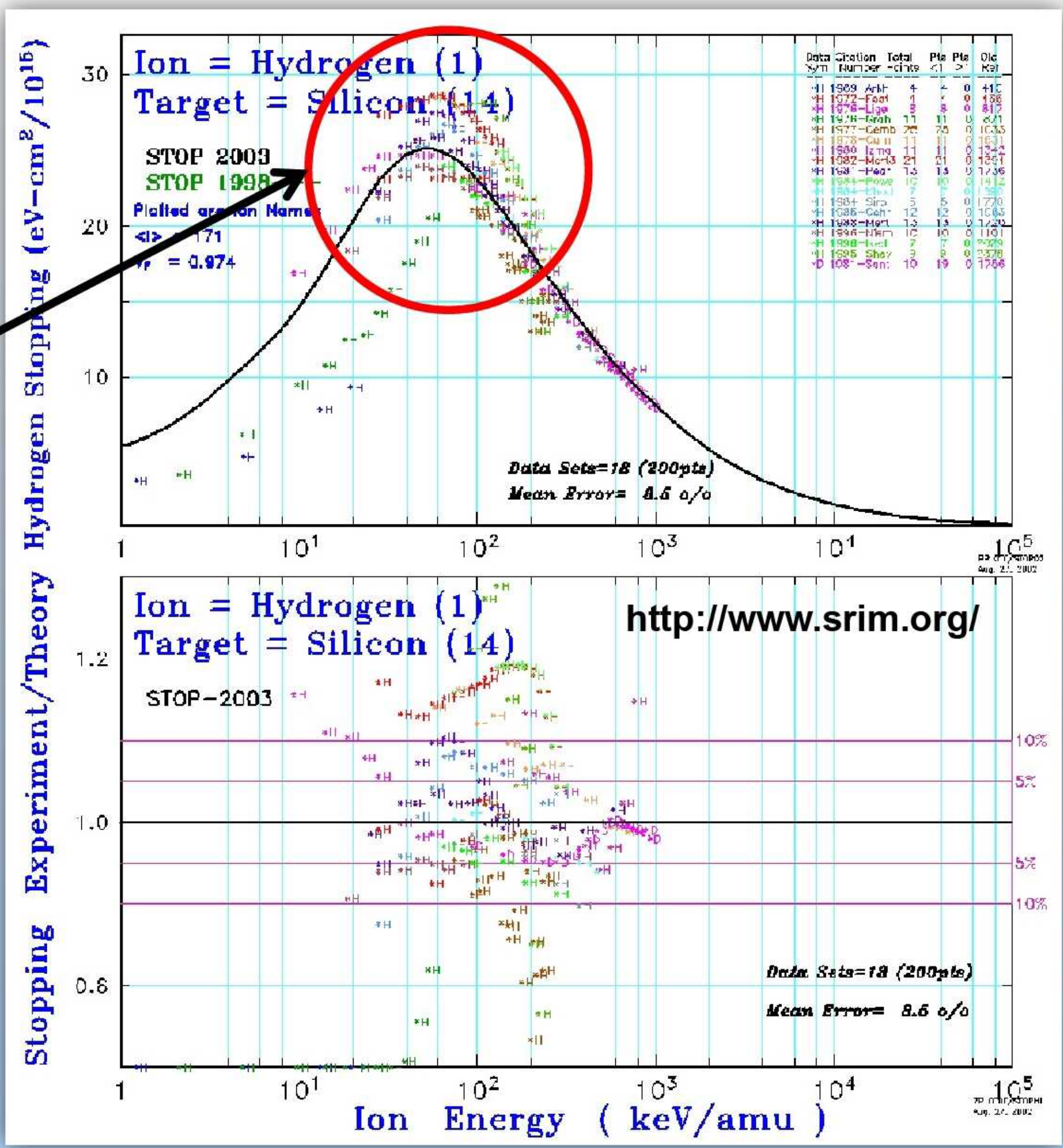


UC Davis Beamline



Proton Stopping Power in Silicon

Variability of stopping power at the Bragg peak



- *d*E/*d*x of interest occurs around Bragg peak
- Systematic complication from both an experimental <u>AND</u> simulation perspective

Proton Transport and Calorimetry

Energy	20.4 MeV	12.5 MeV	6.5 MeV	100 keV
Range_{Si}	2.5 mm	1.1 mm	340 μm	0.87 μm
dE/dx_{Si} ($\text{MeV}\cdot\text{cm}^2/\text{mg}$)	0.02	0.03	0.05	0.5

SRIM-2008 Values

- **Lower energy tune → easier to get more particles of the same energy*****
- **Precision of beam energy tune can be critical (range at 100 keV!!)**

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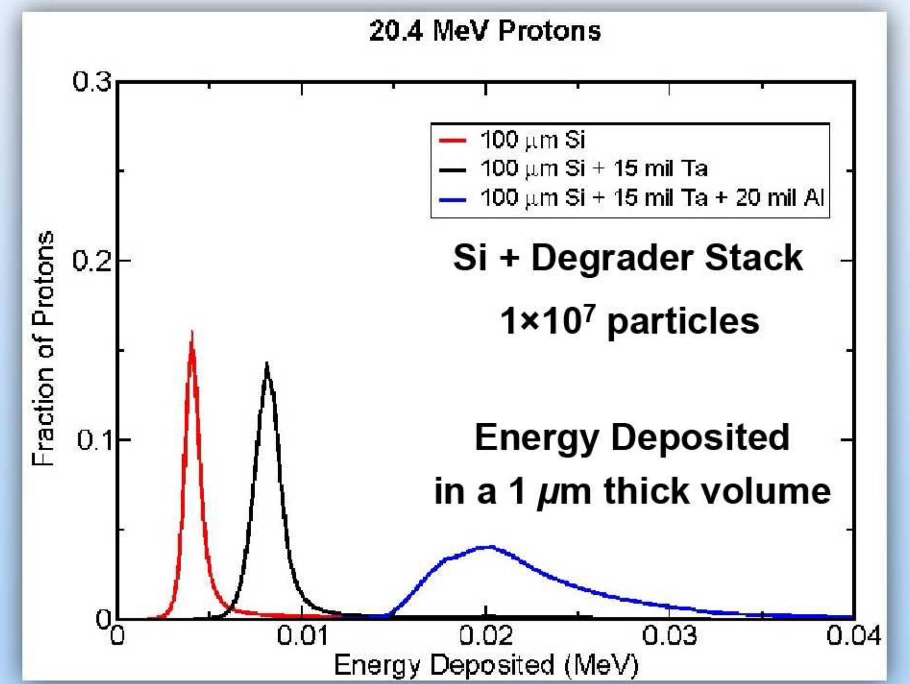

MRED Calculations

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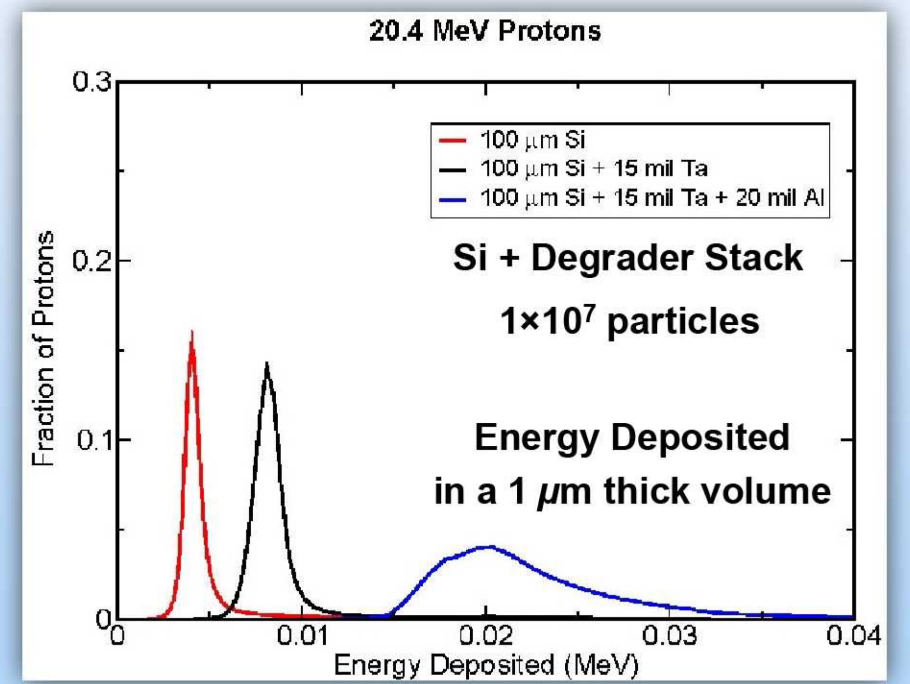
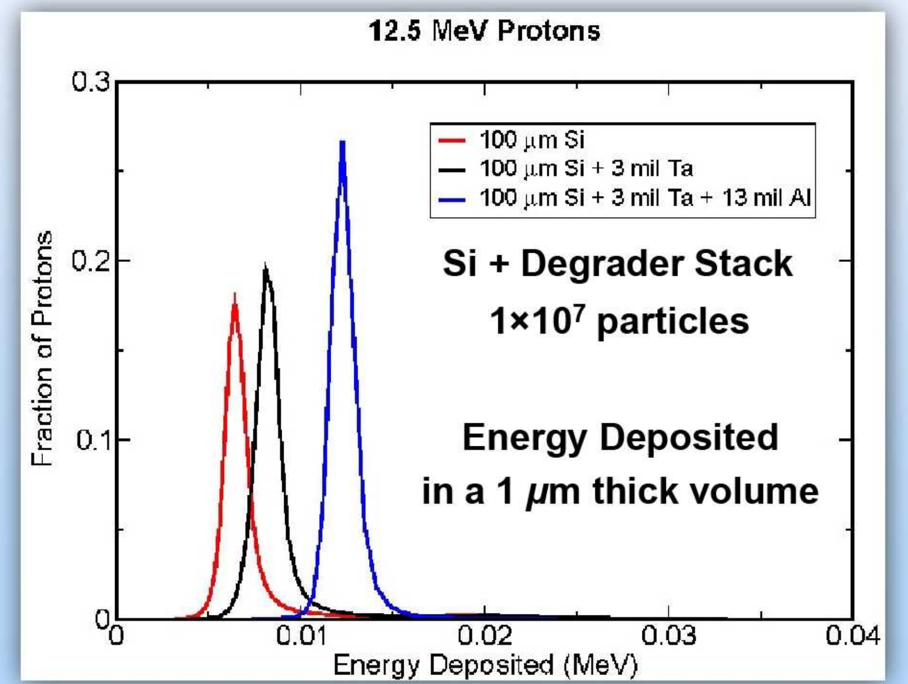
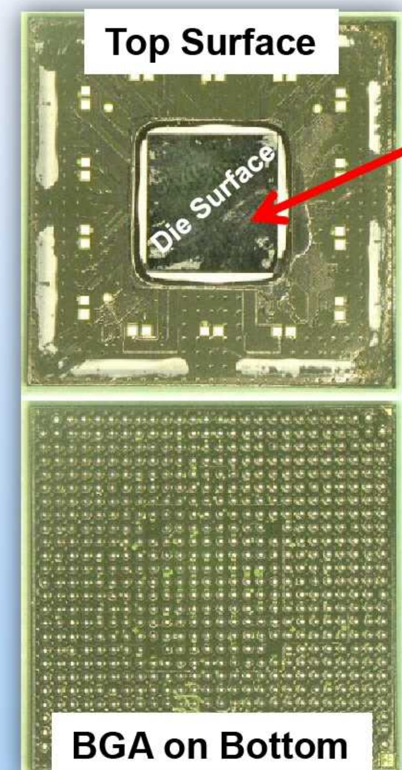


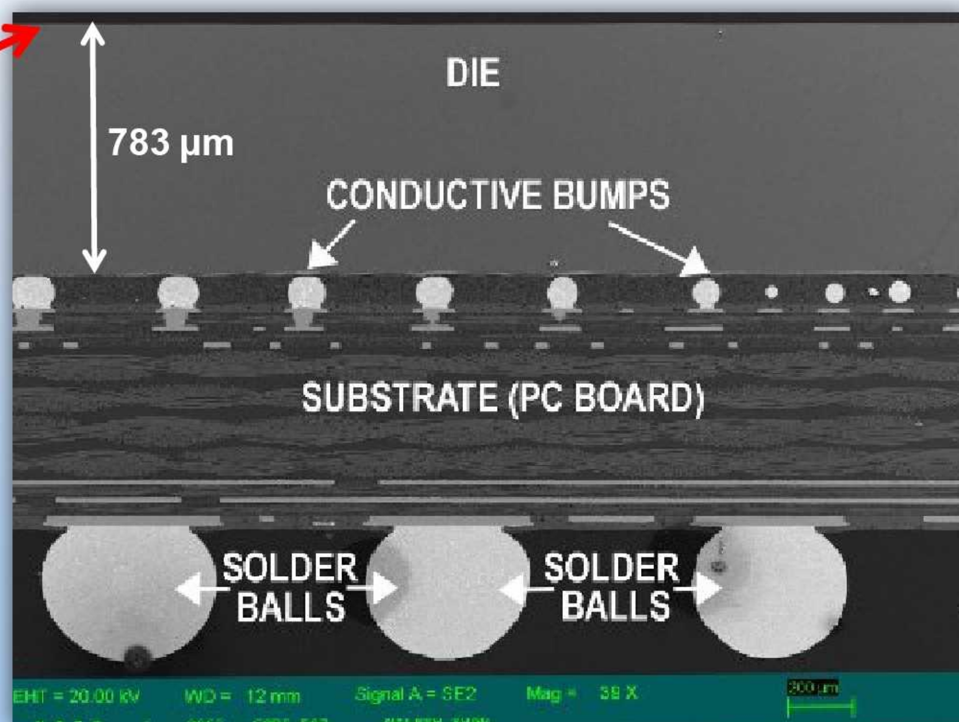


MRED Calculations

Backside Testing – Unthinned DUT

– **Xilinx FPGA, Virtex-IV, LX25**
– **Proton testing conducted at UC Davis Crocker Nuclear Lab**





DPA Cross Section of DUT

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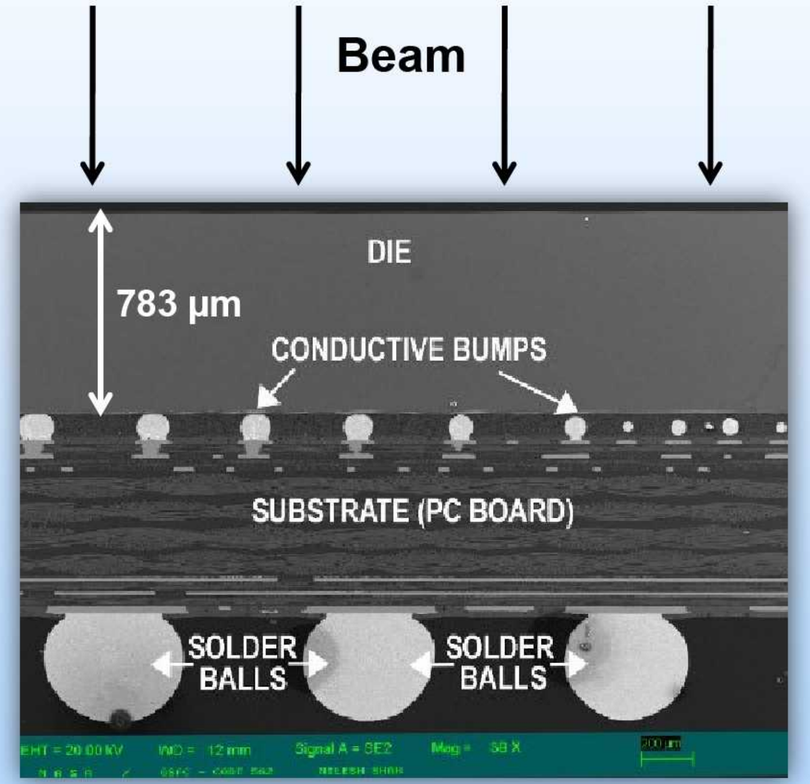
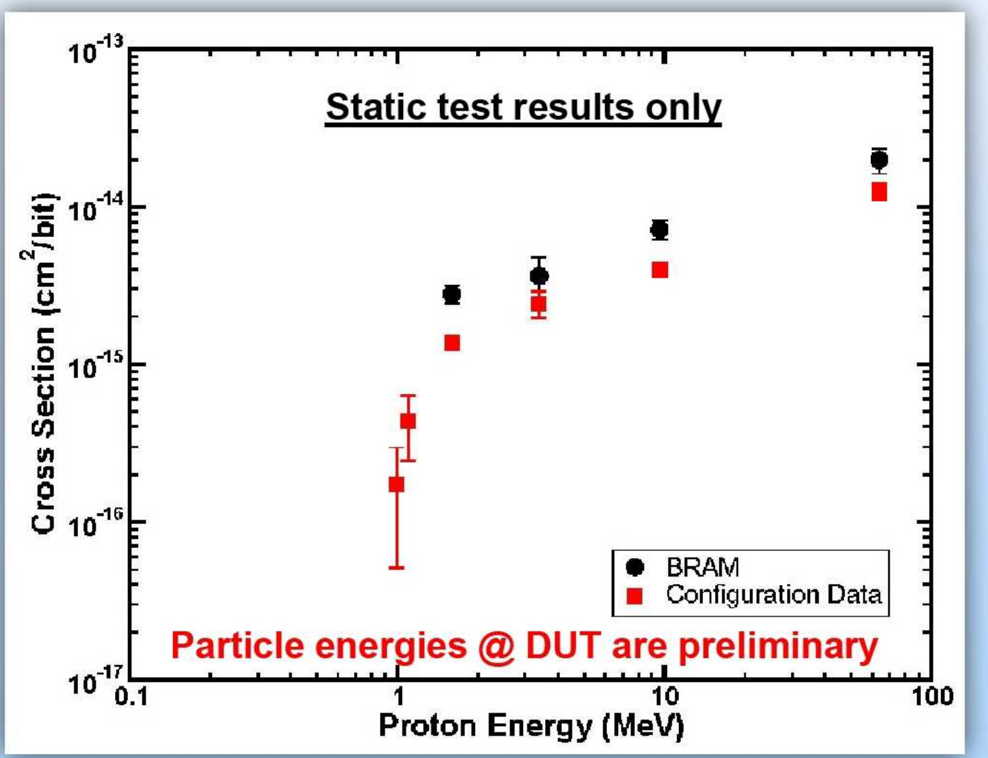


DPA Cross Section of DUT

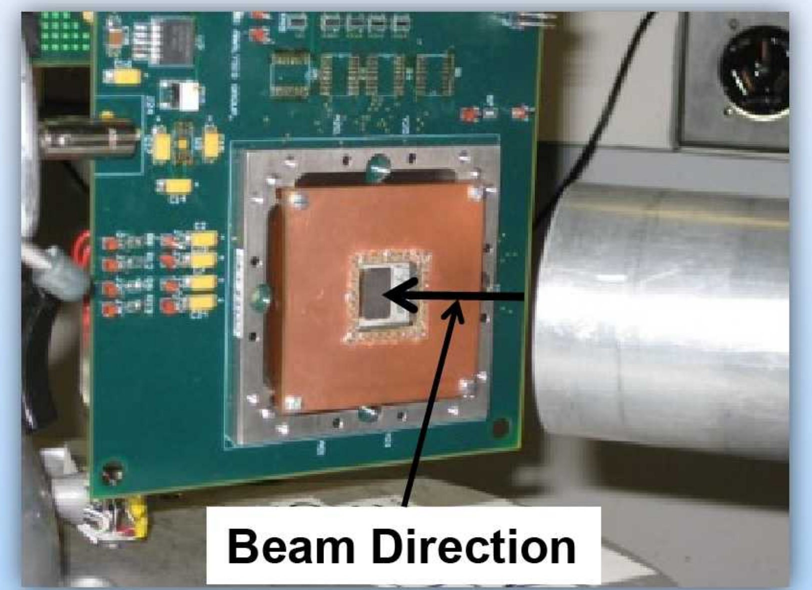
Various Degrader Stacks Used

67.5 and 20.4 MeV Tunes Used



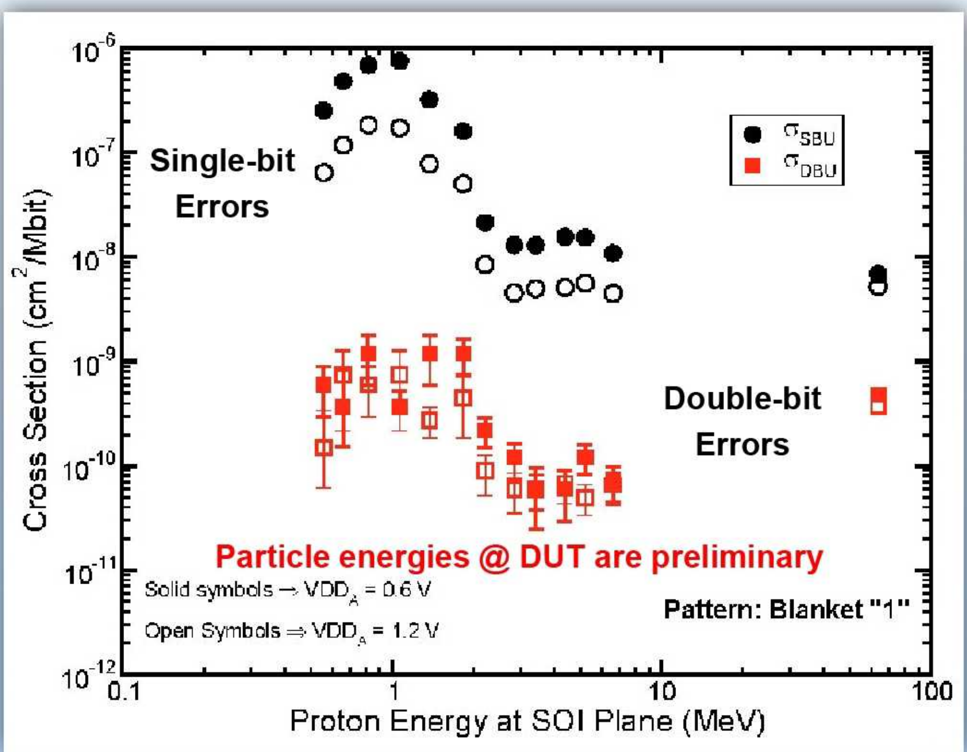
Backside Testing – Thinned DUT

- 36 Mbit IBM Magnum 45 nm SOI SRAM
- Proton testing conducted at UC Davis Crocker Nuclear Laboratory



Various Degrader Stacks Used

67.5 and 20.4 MeV H^+, and ***12.5*** MeV H^+ Tunes Used



D. F. Heidel *et al.*, SEE Symposium, April 2009.

Backside Testing – Thinned DUT

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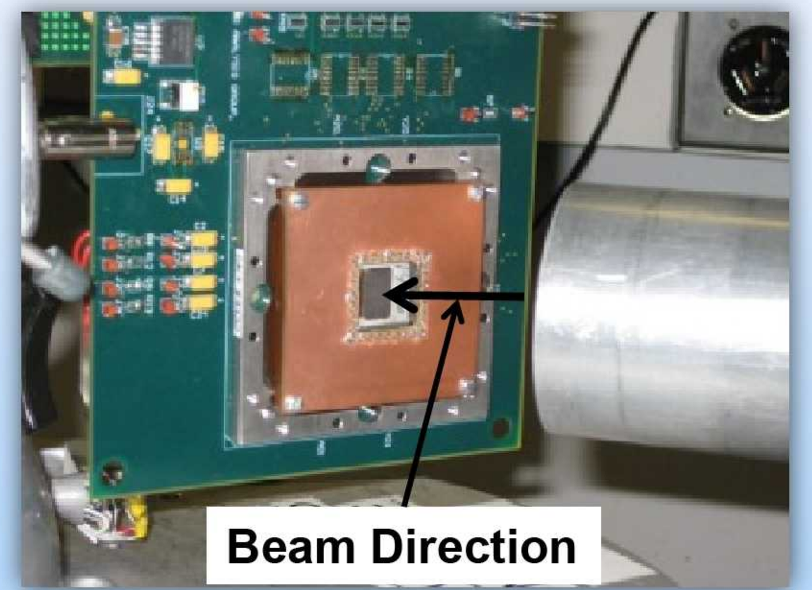
Ideal case would be to have a DUT with no substrate – could just use primary beam (no degraders)



?proton testing in vacuum?

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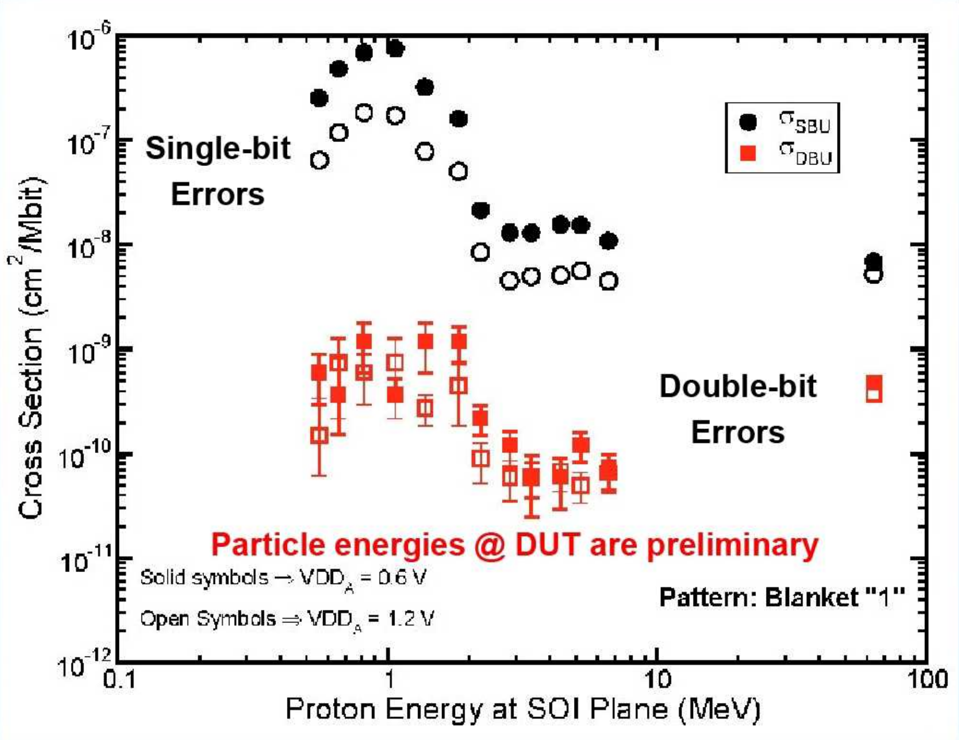


D. F. Heidel *et al*., SEE Symposium, April 2009.

Best-Practices for Low-Energy Proton Testing

- **Record as much detail as possible regarding materials upstream from the sensitive DUT regions**
  - Kapton/aramica windows, degrader foils, air gap, substrate or BEOL thickness, PCBs, package lids, etc.
- **Tune the primary beam energy as much as is feasible to achieve lower particle energy**
  - Don't forget straggle (range AND energy)
- **Remember that there is nearly unavoidable systematic error in proton energy @ DUT plane**
- **Utilize available radiation transport tools to make a best estimate of the particle energy and possible flux attenuation at the sensitive region**

Utility of Low LET Particles

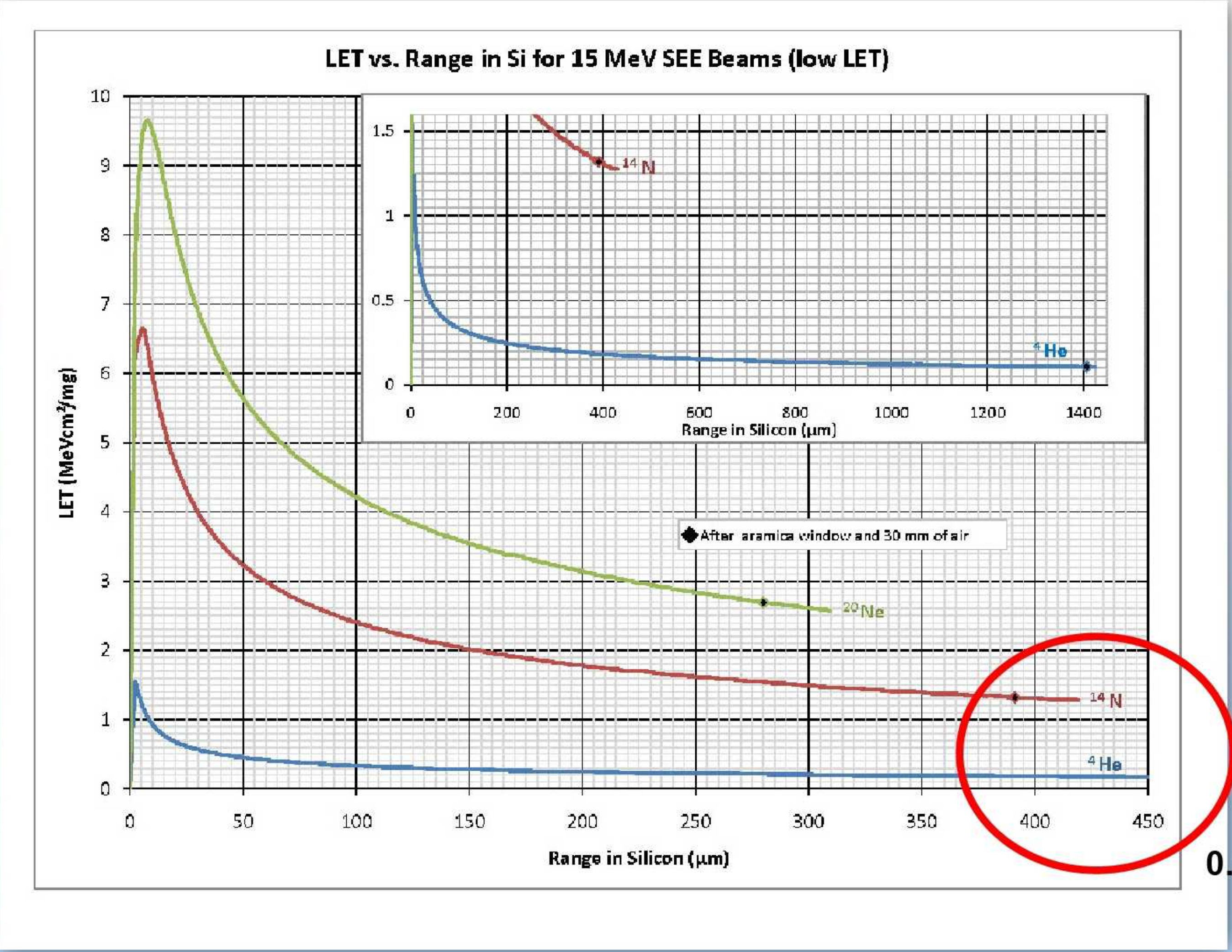
- **Below 90 nm, difficult to investigate single sensitive features**
  - **Multi-cell and multi-bit upsets – cannot distinguish features**
  - **Common example is an SRAM cell**

45 nm		65 nm
0.5 μm^2	***Roughly***	**1.0 μm^2**

Sensitive regions within are even smaller

<u>Question to be answered</u>: do low-energy protons and equivalent-LET heavy ions produce the same cross section?

High-Energy Light Ions

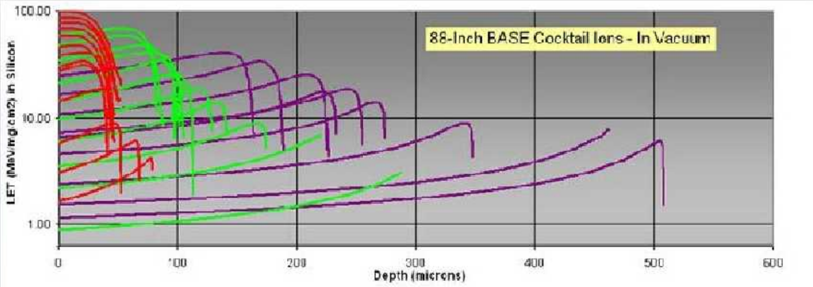


http://cyclotron.tamu.edu/ref/LET_vs_Range_15.pdf

^{4}He @ 0.1 MeV*cm^{2}/mg

TAMU 15 MeV/u tune – He and N also available at 25 and 40 MeV/u

High-Energy Light Ions



Ion	Cocktail (MeV/nuc)	Energy (MeV)	Z	A	Chg. State	% Nat. Abund.	LET 0° (MeV/(mg/cm²))	LET 60° (MeV/(mg/cm²))	Range (µm)	Method
B	4.5	44.90	5	10	+2	19.9	1.65	3.30	78.5	MIVOC
N	4.5	67.44	7	15	+3	0.37	3.08	6.16	67.8	Gas
Ne	4.5	89.95	10	20	+4	90.48	5.77	11.54	53.1	Gas
Si[1]	4.5	139.61	14	29	+6	4.67	9.28	18.56	52.4	Gas
Ar	4.5	180.00	18	40	+8	99.6	14.32	28.64	48.3	Gas
V	4.5	221.00	23	51	+10	99.75	21.68	43.36	42.5	Probe
Cu	4.5	301.79	29	63	+13	69.17	29.33	58.66	45.6	Probe
Kr	4.5	387.08	36	84	+17	17.3	38.96	77.92	48.0	Gas
Y	4.5	409.58	39	89	+18	100	45.58	91.16	45.8	Probe
Ag	4.5	480.50	47	109	+22	48.161	58.18	116.36	46.3	Probe
Xe	4.5	602.90	54	136	+27	8.9	68.84	137.68	48.3	Gas
Tb	4.5	724.17	65	159	+32	100	77.52	155.04	52.4	Probe
Ta	4.5	805.02	73	181	+36	99.988	87.15	174.30	53.0	Probe
Bi	4.5	904.16	83	209	+41	100	99.74	199.48	52.9	Oven
B	10	108.01	5	11	+3	80.1	0.89	1.78	305.7	MIVOC
O	10	183.47	8	18	+5	0.2	2.19	4.38	226.4	Gas
Ne	10	216.28	10	22	+6	9.25	3.49	6.98	174.6	Gas
Si[1]	10	291.77	14	29	+8	4.67	6.09	12.18	141.7	Gas
Ar	10	400.00	18	40	+11	99.6	9.74	19.48	130.1	Gas
V	10	508.27	23	51	+14	99.75	14.59	29.18	113.4	Probe
Cu	10	659.19	29	65	+18	30.83	21.17	42.34	108.0	Probe
Kr	10	906.45	36	84	+24	57	30.23	60.46	113.1	Gas
Y	10	928.49	39	89	+25	100	34.73	69.46	102.2	Probe
Ag	10	1039.42	47	107	+29	51.839	48.15	96.30	90.0	Probe
Xe	10	1232.55	54	124	+34	0.1	58.78	117.56	90.0	Gas
N	16	233.75	7	14	+5	99.63	1.16	2.32	505.9	Gas
O	16	277.33	8	17	+6	0.04	1.54	3.08	462.4	Gas
Ne	16	321.00	10	20	+7	90.48	2.39	4.78	347.9	Gas
Si[1]	16	452.10	14	29	+10	4.67	4.56	9.12	274.3	Gas
Cl	16	539.51	17	35	+12	75.77	6.61	13.22	233.6	Natural
Ar	16	642.36	18	40	+14	99.600	7.27	14.54	255.6	Gas
V	16	832.84	23	51	+18	99.750	10.90	21.80	225.8	Probe
Cu	16	1007.34	29	63	+22	69.17	16.53	33.06	190.3	Probe
Kr	16	1225.54	36	78	+27	0.35	24.98	49.96	165.4	Gas
Xe	16	1954.71	54	124	+43	0.1	49.29	98.58	147.9	Gas
N	30	425.45	7	15	+7	0.37	0.76	1.52	1370.0	Gas
O	30	490.22	8	17	+8	0.04	0.98	1.96	1220.0	Gas
Ne	30	620.00	10	21	+10	0.27	1.48	2.96	1040.0	Gas
Ar	30	1040.11	18	36	+17	0.337	4.87	9.74	576.1	Gas

[1] By Special request

- **LBNL BASE facility 4.5, 10, 16, and 30 MeV/u cocktails.**
- **Note inclusion of ^{11}B at 10 MeV/u and ^{14}N at 16 and 30 MeV/u**
  - **^{3}He available at 16 MeV/u, though not listed**
  - **^{3}He possible at 30 MeV/u, though untested and would require development time**

http://cyclotron.lbl.gov/subpage2.html

Summary

- Use of low-energy protons and high-energy light ions is becoming necessary to investigate current-generation SEU thresholds

- Systematic errors can dominate measurements made with low-energy protons
  - Range and energy straggling contribute to systematic error
    - Not just counting statistics anymore
  - Low-energy proton testing is not a step-and-repeat process

- Low-energy protons and high-energy light ions can be used to measure SEU cross section of single sensitive features – important for simulation